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The Terminal Doppler Weather Radar Tornadic Vortex Signature Detection Algorithm

Program Director
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December 1990

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Interim Report

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16. Abstract

An algorithm for real-time detection of tornadoes, using single-Doppler radar data, is described. This algorithm searches for tornadic vortex signatures (TVS's) which are characterized by strong azimuthal shear in Doppler velocity fields. A TVS usually indicates that a tornado is occurring. The algorithm searches for azimuthal radial velocity differences, above a certain threshold, between adjacent gates at constant range. It then builds these "pattern vectors" into features for each scan in elevation, and finally determines the vertical correlation among features. When at least three features are vertically correlated and the lowest one is below a prescribed minimum-height threshold, a "TVS" is declared, indicating that a tornado is occurring. If the lowest feature is not below the height threshold, a "potential TVS (PTVS)" is declared, indicating that a tornado may soon occur.

The TVS algorithm has been tested on five tornadoes that occurred in Colorado and Missouri. Each tornado had an associated TVS, which was detected by the algorithm. In all cases, either a PTVS or TVS preceded each tornado, resulting in a 4 minute average lead time. Evaluated on a scan-by-scan basis, the Probability Of Detection (POD) is 78%. No TVS false alarms and only 3 PTVS false alarms occurred for these 5 cases. The algorithm was also tested on two rotating microbursts with no detections occurring.

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List of Acronyms

AGL   Above Ground Level

COHO   Coherent Oscillator

FAR   False Alarm Ratio

JDOP   Joint Doppler Operational Project

NEXRAD Next Generation Weather Radar

NSSL   National Severe Storms Laboratory

POD   Probability of Detection

PTVS   Potential Tornadic Vortex Signature

TDWR   Terminal Doppler Weather Radar

TVS   Tornadic Vortex Signature

UTC   Universal Time Coordinated

The TDWR Tornadic Vortex Signature Detection Algorithm

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1. Introduction

It has been known for nearly two decades that a single-Doppler radar can detect wind circulations associated with mesocyclones and tornadoes. During the Joint Doppler Operational Project or JDOP (Burgess et al. 1979), it was found that nearly 50% of mesocyclones observed by the National Severe Storms Laboratory's (NSSL) research Doppler radar were associated with tornadoes.

First termed "gate-to-gate shear" by Burgess et al. (1975) and Lemon et al. (1975), the tornadic vortex signature (TVS) is a good indicator of tornadic activity. The primary feature of a TVS is the large difference between Doppler velocities at adjacent azimuths at the same range. An example of a TVS during the 22 May 1981 Binger tornado (Fig.1) is shown in Figs. 2 and 3. Data are from the Norman Doppler radar operated by the National Severe Storms Laboratory. The tornado occurred about 70 km west of Norman, Oklahoma and was rated F4 on the Fujita intensity scale (Fujita 1981). The width of the tornado at cloud base was nearly 1 mile. A "hook echo" is evident in the reflectivity pattern at 0.4 deg elevation angle just southwest of the main precipitation core (Fig. 2a). The TVS can be recognized in the Doppler velocity field (Fig. 2b) as the region of velocity extrema of opposite signs collocated with the hook echo. Maximum velocities exceed the 32 m s^{-1} Nyquist velocity as evidenced by the aliasing in the region of the TVS moving toward the radar. De-aliased radial velocities along beams penetrating either side of the TVS at 0.4 deg elevation angle 6 min earlier are shown in Fig. 3 (from Burgess an Lemon 1989). Additional data not shown have been contoured. The TVS is very strong with a maximum azimuth-to-azimuth velocity difference of 114 m s^{-1}. The shaded region encompasses those velocity pairs, referred to later as pattern vectors, which comprise a "feature" in the TVS algorithm (see Section 2 for details).

The key algorithm parameter for TVS detection is the velocity difference between two adjacent gates at the same range (see Section 2 for a more detailed discussion of the algorithm structure). As Brown et al. (1978) points out, TVS detection is primarily a function of the ratio of radar beamwidth to core radius of the tornado; the radar beam linearly widens with increasing range and the TVS positive and negative velocity extrema are smoothed out. Burgess and Lemon (1989) showed that, for a

Figure 1. Photograph of the 22 May, 1981 Binger tornado.

beamwidth-to-core-radius ratio of 5 (assuming a 1° beam), actual tangential velocity peaks of 50 m s⁻¹ would be detected by the radar as only 20 m s⁻¹ peaks. In the case of a 100-meter wide tornado at 60 km range, the beamwidth-to-core-radius ratio is 10, and the 50 m s⁻¹ tangential velocity peaks would be reduced to 10 m s⁻¹. The gate-to-gate velocity difference would be 20 m s⁻¹, barely above the 17 m s⁻¹ threshold adopted for the TVS algorithm (aside from other TVS detection criteria).

It must be remembered that the Binger tornado represents the upper end of the spectrum of tornado sizes and intensities. Some of the smaller tornadoes may not produce a detectable signature even within the relatively close TDWR horizontal range limit of 60 km. In order to get a better idea of what the range limitations are, a large TVS data base representing a wide range of tornado types is being compiled for future algorithm testing.

This paper describes a real-time algorithm for TVS detection using single-Doppler weather radar data. The algorithm was developed for the Terminal Doppler Weather Radar (TDWR) program (Turnbull et al. 1989) and is a modification of the NEXt generation weather RADar program (NEXRAD) mesocyclone algorithm (Zrnic' et al. 1982). The primary difference between the two algorithms is that the mesocyclone algorithm searches for velocity differences over several azimuths whereas the TVS algorithm is limited to adjacent radials. A check for vertical continuity of features at different
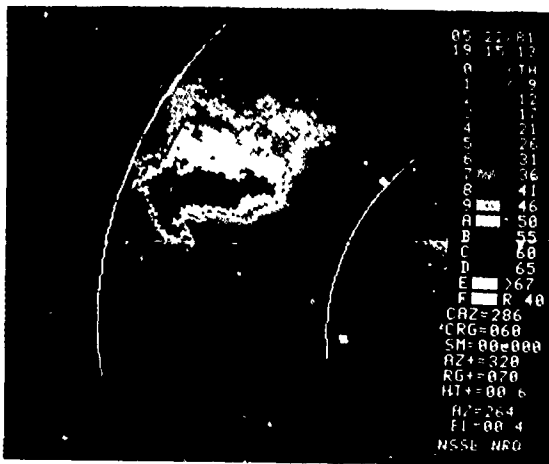
a)
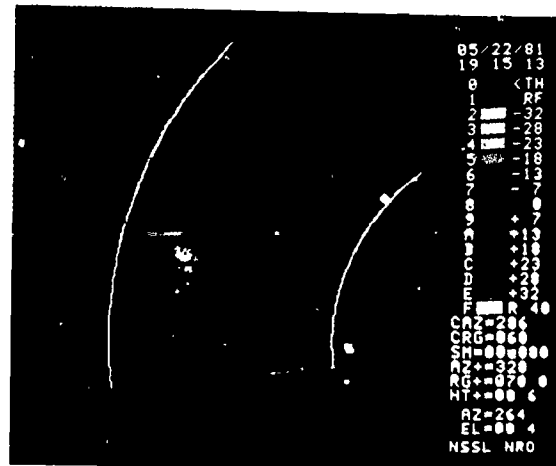
b)

Figure 2. Displays from NSSL's Norman Doppler radar at 1915 CST, near the time of the tornado in Fig. 1, of a) reflectivity (dBZ) and b) radial velocity (m s^{-1}). Range rings are every 40 km. Color scales for reflectivity and velocity are at the right in their respective frames. Elevation angle is 0.4 deg.
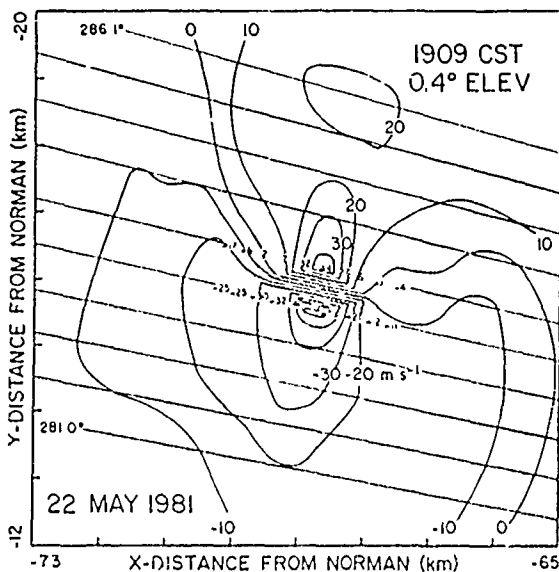

Figure 3. Plot of selected Doppler radial velocities from a 0.4 degree elevation angle scan at 1909 CST. Plotted velocities as well as data not shown are contoured at 10 m s^{-1} intervals. The TVS at this scan is shaded.

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elevation angles has been added and is described herein. As will be shown later, an important aspect of the vertical-continuity requirement is that false alarms are significantly reduced. The algorithm structure is described in Section 2. The TVS algorithm was tested on TDWR-format Doppler radar data collected during four tornadoes in Colorado and one in Missouri with the results outlined in Section 3. Section 4 contains a summary and a description of future work.

2. Algorithm Structure

Figure 4 shows the block diagram for the TVS algorithm. After passing through system clutter and dealiasing algorithms (see Turnbull et al. 1988), the data are thresholded to remove low signal-to-noise ratios and low reflectivity values (see Table 1 for current threshold values). They are then smoothed with a 3-point filter along each radial. Once two radials of data have been obtained, an azimuth-to-azimuth comparison of velocities at a constant range is done. The algorithm searches for only cyclonic shear, as anti-cyclonic tornadoes are rare (although the algorithm could be modified to do so). In addition, only data below 6.0 km above ground level (AGL) (an adjustable parameter) are used in order to cut down on computer processing time. When the azimuth-to-azimuth velocity difference exceeds a threshold (see Table 1), a 5-element pattern vector array is created. The pattern vector array, as stored in the computer, consists of beginning and ending velocity, beginning and ending azimuth, and range. As seen in Fig. 3, the velocity pair consisting of the $- 70$ m s^{-1} and $+ 44$ m s^{-1} radial velocities, as well as their respective azimuths and range, constitute a pattern vector.

Once the entire tilt (constant-elevation scan) has been processed, the pattern vectors are grouped into features. To be included in a feature, at least three pattern vectors must be within 0.5 km of each other in range and their azimuthal centers must be no more than 1.5 degrees apart. Features with a length-to-width ratio greater than 4 are eliminated from further consideration, as they are likely associated with phenomena other than tornadoes, such as shear segments along radially-oriented gust fronts. The following attributes of the remaining features are then calculated: center azimuth, center range, height, and average velocity difference.

After all tilts have been processed, the features are sorted according to height and vertically correlated which begins by comparing the next-to-lowest feature to the lowest "reference" feature. If the next-to-lowest feature is within a 2.5 km radius (an adjustable parameter) of the reference feature, it becomes the reference feature and is compared to the next-higher feature. The process continues until the highest feature has been considered. The algorithm then starts over with the lowest feature that was not vertically correlated with any other feature (i.e., not within 2.5 km radius of the first reference feature) and the whole process is

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repeated. A "TVS" product is created when three or more features are vertically correlated, with the lowest feature being below a prescribed height above the ground. A "potential TVS (PTVS)"
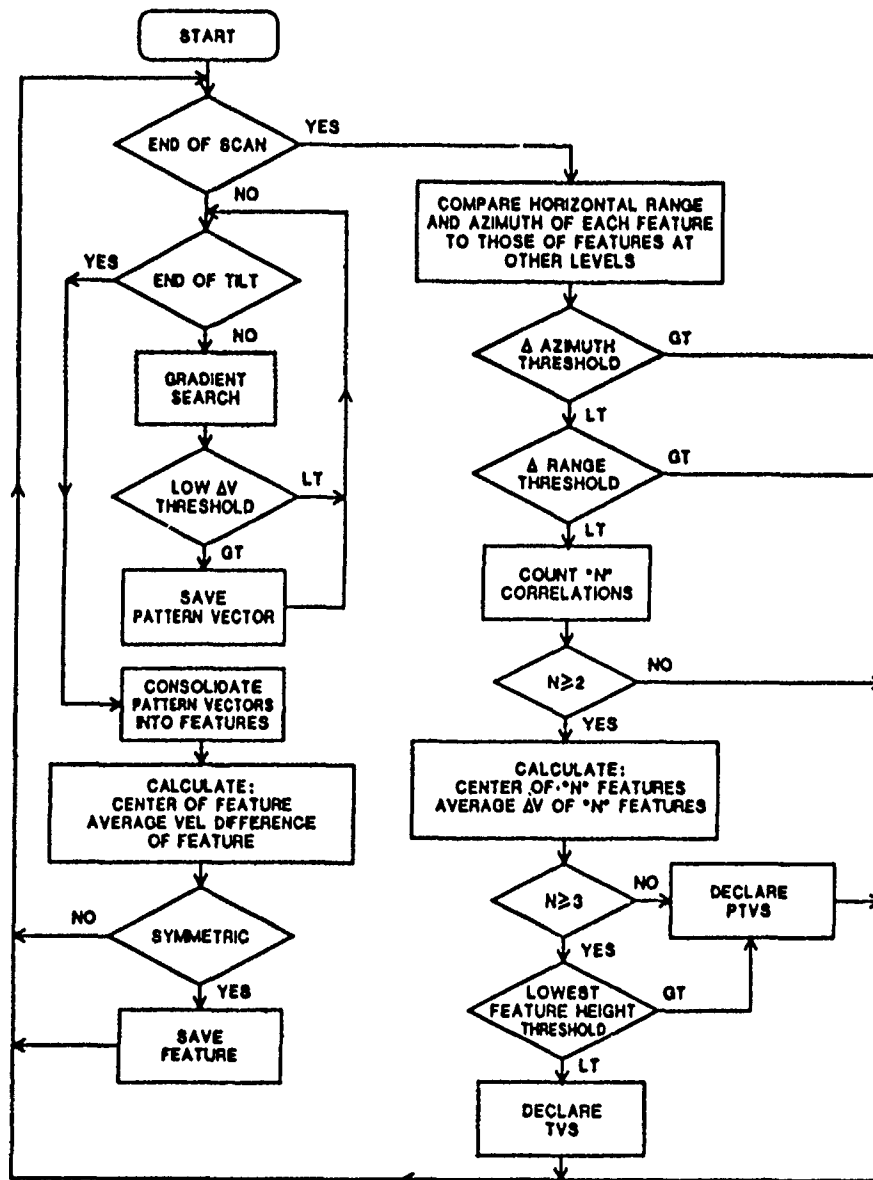

Figure 4. TVS algorithm block diagram.

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product is created when three features are vertically correlated but the lowest feature is above the minimum-height threshold. Algorithm output is generated every 2.5 min and consists of the x-y coordinates of the TVS's and PTVS's whereby a graphics symbol may be displayed.

Range-folded echoes and ground clutter may result in features that can be mistaken for TVS features. These false alarms are typically confined to the lowest one or two tilts and can be

PARAMETER	VALUE
MINIMUM AZIMUTHAL VELOCITY DIFFERENCE	17 m s^{-1}
MINIMUM NUMBER OF PATTERN VECTORS IN A FEATURE	3
MINIMUM NUMBER OF FEATURES IN A TVS OR PTVS	3
MAXIMUM LENGTH-TO-WIDTH RATIO OF FEATURE	4
MINIMUM HEIGHT OF LOWEST FEATURE IN A TVS	0.6 km
MINIMUM RANGE FOR DATA PROCESSING	5 km
MAXIMUM RANGE FOR DATA PROCESSING	60 km
MAXIMUM HEIGHT FOR DATA PROCESSING	6.0 km
MINIMUM SNR FOR DATA PROCESSING	0 Db
MINIMUM REFLECTIVITY FOR DATA PROCESSING	0 DBZ
MAXIMUM HORIZONTAL RADIUS FOR VERTICAL CORRELATION	2.5 km

Table 1. Thresholds/parameters for the TVS algorithm.

eliminated from consideration by requiring that they be correlated with features aloft.

3. Algorithm Performance

The TVS algorithm was tested on TDWR-format Doppler radar data collected during five tornadoes and two rotating microbursts, with the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) TDWR testbed Doppler radar. Four of the tornadoes occurred on June 15, 1988, near Denver, CO, with three of them occurring simultaneously. The fifth tornado occurred south of Kansas City, MO, on May 25, during the 1989 TDWR demonstration when the algorithm ran in real-time. All the Denver tornadoes are documented in Storm Data (NOAA, 1988) and were associated with at least some reported damage. Reports from local storm spotters have been used to augment Storm Data. The Kansas City tornado was confirmed by the Missouri State Highway Patrol as having a brief dust swirl, but no reported damage.

The algorithm was evaluated on a scan-by-scan basis with any detection, TVS or PTVS, occurring not more than 20 min prior to the observation of either a tornado or funnel cloud considered a "hit". It was found during JDOP that twenty minutes was the average time between tornado advisories, based partly on Doppler velocity signatures, and tornado "touchdown". Any non-detection occurring during a reported tornado is considered a "miss", and a detection not associated with a tornado is a "false alarm". Because of the large uncertainty associated with visual identification of severe weather phenomena, especially by poorly-trained or casual observers, performance statistics must be interpreted with caution. Indeed, even a highly trained spotter may not be able to distinguish between a funnel cloud and a tornado.

A Doppler velocity field at 2214 UTC on June 15, 1988 from the FL-2 radar is shown in Fig. 5. The elevation angle is 0.5 deg. At this time, 2 tornadoes (numbers 3 and 4 in Fig. 5) are occurring and are associated with TVS's (see Fig. 6 and related discussion). A third (number 2) is about to form and a fourth (number 1) has just dissipated. Note that the maximum azimuth-to-azimuth velocity differences in the TVS's are only 25 - 30 m s^{-1}, very weak compared to the 114 m s^{-1} measured for the Binger tornado (which was 3 times as far away from the radar).

All four tornadoes on June 15 formed along a convergence boundary caused by colliding thunderstorm outflows. The boundary can be visualized in the velocity field as the line of velocity convergence beginning about 20 km west of the radar and extending northeastward. Recent studies of High-Plains tornadoes (see e.g., Brady and Szoke 1989) have shown that the tornadoes are typically confined to low altitudes as vorticity perturbations along convergence boundaries are entrained into thunderstorm updrafts and amplified through stretching. This type of tornado has been referred to as a non-[midlevel] mesocyclone or non-supercell tornado. In contrast, the Binger tornado was associated with a
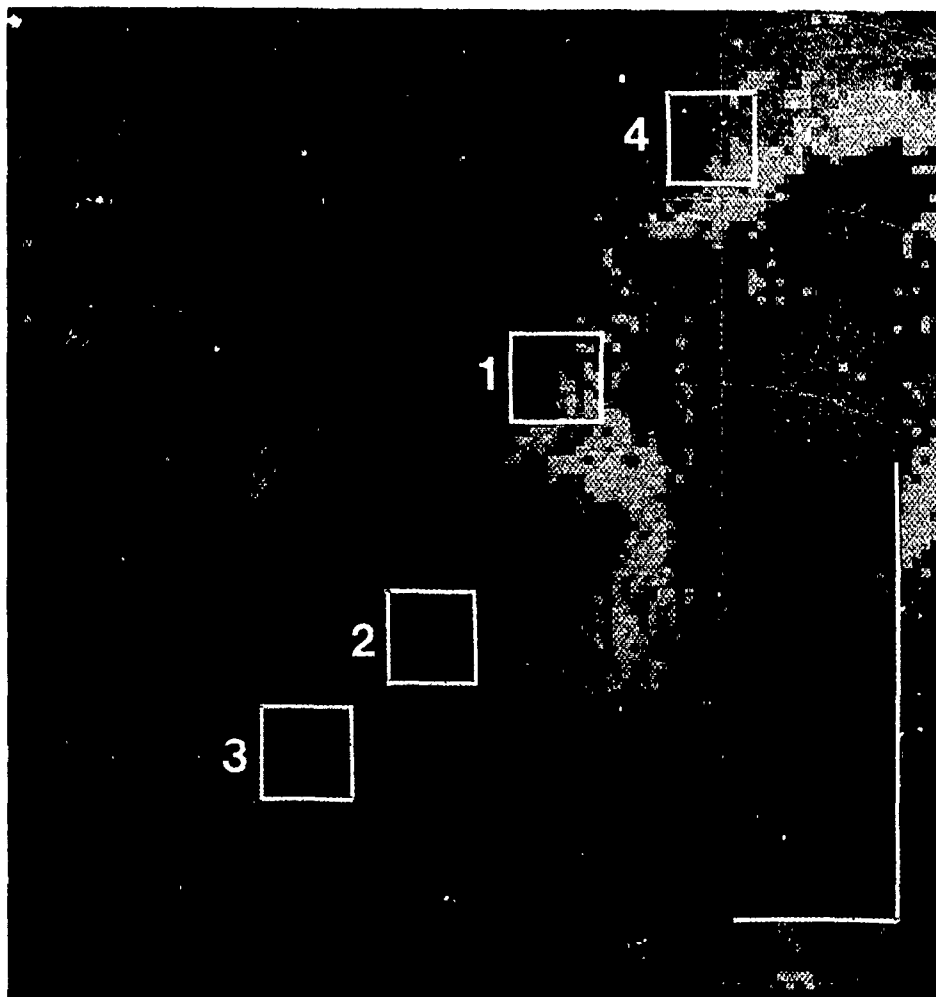
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Figure 5. Doppler velocity display from the FL-2 radar at 2214 UTC on June 15, 1988. Range rings are every 20 km; elevation angle is 0.5 deg. Numbered squares indicate signatures referred to in the text.

strong midlevel mesocyclone.

The time history of algorithm output for the five tornado cases along with the duration of reported tornadic activity is shown in Fig. 6. Tornado 1 formed 20 km NNW of FL-2 and was rated F1 on the Fujita intensity scale. The TVS algorithm declared a TVS 2.5 min prior to the tornado's touchdown. The tornado lasted only 6 min but produced a detectable signature its entire lifetime. The last declaration for the tornado was a PTVS indicating that the tornado had become too small or weak to be detected at the lowest tilt.

Tornado 2, rated F2, produced a spectacular funnel that caused brief evacuation of non-essential personnel from the control tower at Stapleton International Airport (approximately 17 km WNW of FL-

2). The dashed line segment for tornado 2 indicates times when only a funnel cloud was observed. A PTVS was declared by the algorithm 8 min prior to tornadic activity but coincidentally with observation of the funnel cloud. Detection by the algorithm continued until just before the last report of the tornado although the funnel lasted another 5 min. The X's indicate that there were three volume scans when the funnel was not detected (i.e., misses).

Tornado 3 (F3) did the most damage of the four as it passed through south Denver, just beyond 20 km from FL-2. The first detection by the algorithm occurred 10 min before the tornado was
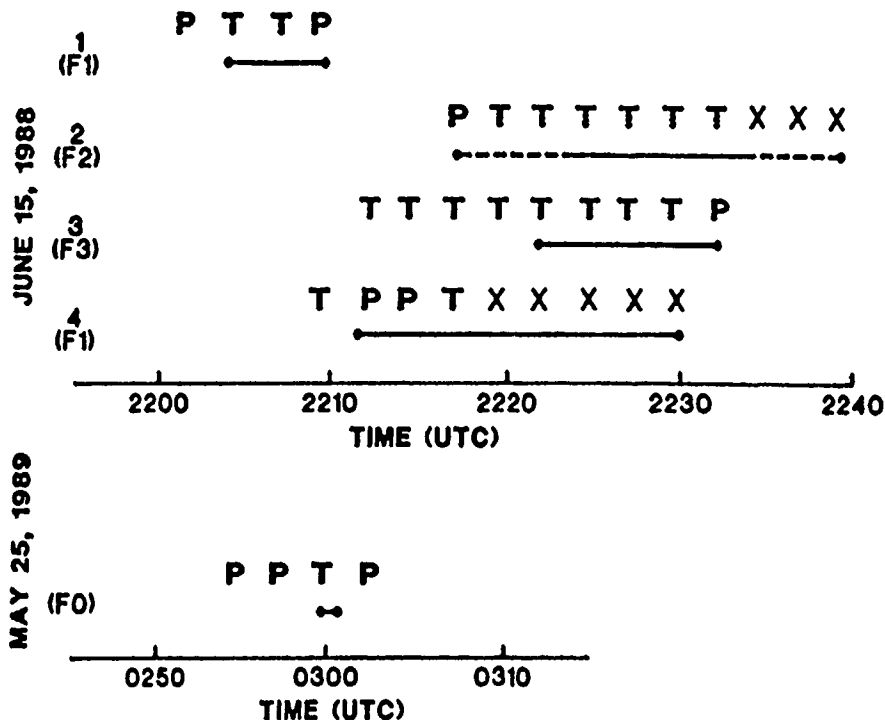

Figure 6. Time history of TVS algorithm output ("T" for TVS;"P" for PTVS) for the June 15, 1988 and May 25, 1989 tornadoes. Lines below algorithm output correspond to actual tornadic activity (see text for details). The dashed line segment for tornado 2 indicates times when only a funnel cloud was observed and the X's indicate missed detections.

first observed. As for tornado 2, detections continued right up until the time tornado 3 dissipated.

The fourth tornado (F1) formed about 31 km north of FL-2, the farthest away of all 4 tornadoes. The algorithm began detecting the TVS 2.5 min prior to its touchdown. Detections ceased at about 2220 UTC when the TVS was obscured by 2nd trip echoes resulting in four missed detections. It is thought that the algorithm declared PTVS's instead of TVS's because of degraded resolvability owing to
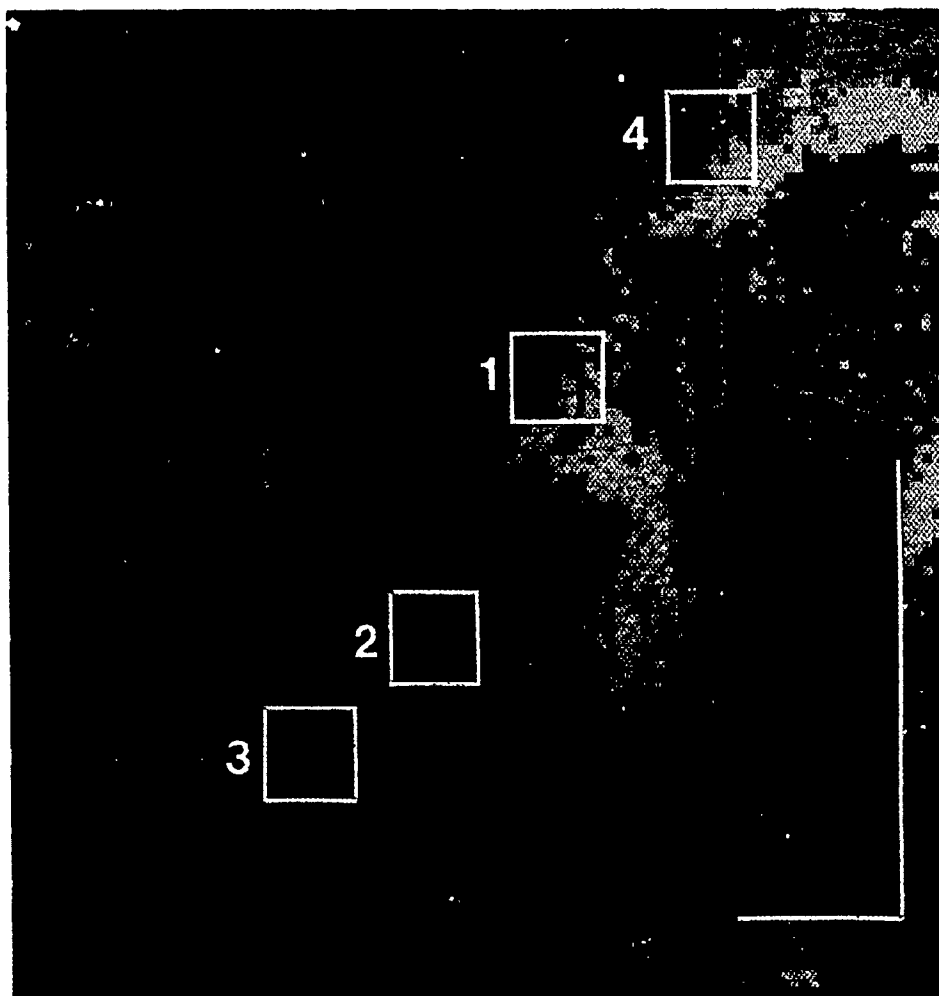
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The TVS algorithm was run in real-time for 5 months on the MIT/LL TDWR prototype radar during the 1989 real-time demonstration and during most of the summer of 1990 in Orlando, FL. In 1989, there were several false alarms, primarily the result of noisy data from the coherent oscillator (COHO). No false alarms were observed in Florida nor were there any detections. The major differences between algorithm performance in Missouri and Florida are that the COHO was not used in Florida and that the reflectivity threshold was increased from -100 dB to 0 dB.

The TVS algorithm was also tested on two microburst cases, June 25, 1988 and August 28, 1989, each associated with midlevel rotation. There was concern that the rotation would cause false alarms. However it was found that the maximum velocities associated with the midlevel rotation, although fairly strong, were spread out over several azimuths resulting in weak gate-to-gate velocity differences and thus were not detected by the algorithm.

4. Summary

The TVS algorithm described herein has a basic structure very similar to the NEXRAD mesocyclone algorithm. However, TVS pattern vectors consist of large azimuthal velocity differences between two adjacent gates at the same range, whereas mesocyclone algorithm pattern vectors may extend across several azimuths. Pattern vectors are then gouped together on individual tilts to form features. A TVS is declared, indicating that a tornado is occurring, when at least 3 features are vertically-correlated with the lowest one below a minimum-height threshold. A PTVS is declared if three features are vertically-correlated but the lowest one is above the minimum-height threshold. Output is generated every 2.5 min.

| | 6/15/88 | | | | 5/25/89 | |
	1	2	3	4	1	TOTAL
POD	4/4	7/10	9/9	4/9	4/4	28/36 (78%)

Table 2. POD statistics (for both TVS's and PTVS's) on a scan-by-scan basis for the five tornadoes.

Preliminary testing on five tornado cases, on a scan-by-scan basis, resulted in 28 hits and 8 misses for a probability of detection (POD) of 28/(28+8) = 78 % (see Table 2). Five of the missed detections were the result of 2nd trip echoes obscuring the TVS. There were 3 PTVS false alarms on June 15, 1988 and no TVS false alarms. There were a number of false alarms during the 1989

demonstration. However, due to experimentation with various hardware devices (e.g., the COHO), data quality is unknown. Since a very low reflectivity threshold (-100 dB) may have allowed noisy data into the algorithm in 1989, this threshold was increased to 0 dB in 1990. No false alarms of any kind occurred in Florida. Preliminary false alarm ratios (FAR) based on data used in the test mode are 0 % and 27 % for TVS's and PTVS's, respectively. The average lead time for all five tornadoes was 4 minutes.

Further testing and modifications to the TVS algorithm are currently underway. A time continuity check is being implemented that may provide tracking and early-warning of tornadoes with a reduction in the PTVS FAR. In addition, time continuity will allow a TVS to be declared if only two features are vertically-correlated (with the lowest feature below the minimum-height threshold). This is important in areas where only two low-level tilts are available, such as outside of the airport surveillance sector in the TDWR scan strategy. Further refinement of vertical continuity requirements and adaptable parameters is underway. Also, testing on many more cases is necessary to have confidence in algorithm output statistics.

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